REFERÊNCIA

OLIVEIRA, T. A. A. et al. Multiscale analysis of multiple cracks in aircraft fuselage. In: IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING, 39., 2018, Paris; Compiègne. **Proceedings** [...], Compiègne: University of Technology Compiegne – Sorbonne Universités, 2018. Disponível em: http://bibliotheque.utc.fr/EXPLOITATION/doc/IFD/IFD_REFDOC_0008926/cilamce-2018-proceedings-of-xxxix-ibero-latin-american-congress-on-computational-methods-in-engineer. Acesso em: 29 mar. 2019.

MULTISCALE ANALYSIS OF MULTIPLE CRACKS IN AIRCRAFT FUSELAGE

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Abstract. This paper consists of the multiscale analysis via Dual Boundary Element Method (DBEM) of fatigue life in riveted aircraft fuselage. First considers the macro analysis in which the fuselage panel is modeled at BemLab2D to obtain the Stress Intensity Factor (SIF) near a rivet. With the SIF, the stress field is then computed in a micro element composed of pre-established initial cracks and holes. This micro analysis was considered in three different positions (θ=0°, θ=45°, θ=90°) and analyzed the crack growth via Dual Boundary Element Method (DBEM) through BemCracker2D. As a result, there is a relationship between fatigue life (number of load cycles) and compliance of the edges of this micro element each crack increment.

Keywords. Multiscale analysis, Fatigue life, Aircraft fuselage, Dual Boundary Element Method.

1. Introduction and Motivation

All structures with free surface are subject to fatigue with cracks starting from the surface and growing until it reaches critical size for fragile rupture, even those subjects only to permanent loads [1]. Unlike structures that are plastically overloaded, in which there are large deflections, rupture caused by fatigue occurs suddenly without warning. Based on this, information relating the variable load over time and particularly its effects on cracks are of fundamental importance for predicting the behavior of the structure as a whole. The *Linear Elastic Fracture Mechanics* (LEFM) then appears as a powerful tool to evaluate crack-tip fatigue in the Small Scale Yielding condition [2]. In an aircraft panel, to determine the parameters of Fracture Mechanics such as Stress Intensity Factor (SIF), is difficult because of the complex nature of the frame of the structure where the details of the frame, spars, shearing clips, rivets, etc., have important role in the nature of the damage process and the possible propagation of any cracks, especially under dynamic loads such as fatigue. In the case of aircraft structures, it is estimated that about seventy per cent of the fatigue cracks originate from the riveted joint holes [3].

Over the years several design philosophies to fatigue have been developed trying to ally structural safety and economy in the process of manufacturing and operating the aircrafts. The first approach was called safe-life. Its philosophy is to design and manufacture a safe aeronautical structure throughout all its lifespan. For this, consider in the prototype tests the most extreme situations of fatigue loads, anticipated during operation. Such methodology results in factors that oversize the structural elements so that there is no possibility of failure. This approach evidently leads to high project costs and is not capable of ensuring safety in the event that an unforeseen project failure occurs during the life of the project.

Rationally, a new philosophy was developed based on the concept of tolerance to harm. In this, it is assumed that the structure, even damaged, is capable of supporting the actions for which it was designed, until the detection of a crack by fatigue or other defect during operation. The structure is then checked, repaired, and restarted until the end of its lifespan. Thus, this approach aims to detect cracks, by inspection, before their growth leads to severe structural failure. That is, it implies knowing the process of crack propagation, determining how many fatigue load cycles are required for the crack to reach a final length, pre-established in the design of the project.

In this way, designers are always looking for quickness, reliability and accurate average data of fracture parameters. Automation appears as a key to evaluate a significant number of analysis as part of parametric studies and optimization of projects [4].

Thus, this paper shows an analysis of multiple cracks in an aircraft fuselage through the automation in software specialized to evaluate the cracks propagation - BemCracker2D [5, 6]. The first analysis refers to the macro element in which is performed a rivet modeling at the software BemLab2D [7] and analyzed via Dual Boundary Element Method the SIF at BemCracker2D. With the SIF, the stresses in a micro element are then calculated. This micro element is composed by two pre-established initial cracks and a circular hole. As a result, there is relationship between fatigue life (number of load cycles) and compliance of the edges of this micro element at each crack increment.

2. Objectives

The main objective is evaluating the compliance of micro elements under several levels of loads, cracks, and holes. And as specific objectives: obtaining edge displacements at each crack propagation and the number of loading cycles for each increment.

3. Material and Methods

Airframe structures, specifically the fuselage, use the 2024 aluminum alloy as a base material because of its high capacity to withstand damage, good mechanical strength and to corrosion [8]. The material considered for the panel was aluminum alloy 2024-T3, yield limit and resistance limit 338 MPa and 476 MPa respectively, Young's modulus and Poisson's coefficient of 74 GPa and 0.33 respectively, and fracture toughness (Kc) 34 MPa√m [9].

The methodology of this paper consists of the analysis via Dual Boundary Elements Method of fatigue life of aircraft fuselage with two cracks pre-established and a circular hole. For this, an aircraft fuselage panel model, representing the macro analysis, was automated in order to obtain elastic stresses in the regions of these voids.

3.1. Validation of the macro model

According to Sanford [10] the model to represent aircraft fuselage is showed in Figure 1. At this model, the rivets are represented as cracks. For this one the analytical SIF is:

$$K = \sigma\sqrt{\pi a}\sqrt{\frac{W}{\pi a}\tan\frac{\pi a}{W}} \tag{1}$$

where σ is the applied load (to this validation σ = 1 MPa), a is the half crack size, W is the distances between of the cracks.

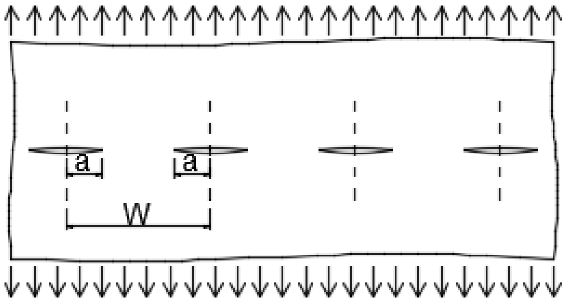


Figure 1: Idealization of the riveted construction of an aircraft fuselage.

BemLab2D was used to create the boundary element mesh to represent the numerical model (see Figure 2), and the BemCracker2D to compute the SIF.

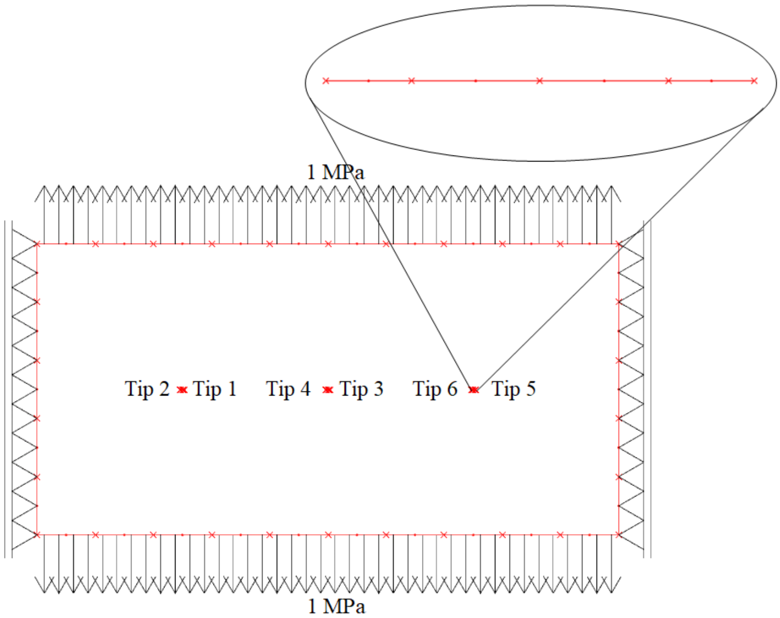


Figure 2: Boundary element mesh of the macro model with BemLab2D.

As result, the SIF values are listed in Table 1.

Analytical	**Numerical**					
	Tip 1	Tip 2	Tip 3	Tip 4	Tip 5	Tip 6
0.07092803	0.07155231	0.07155169	0.07156367	0.07156367	0.07155169	0.07155231

Table 1: Analytical and numerical SIF results.

These results therefore present the purpose of corroborating the model and the subsequent analysis to be performed.

3.2. Analysis of the micro model

With the SIF computed, the stress field at the crack tip is calculated through the Eqs. (2), (3) and (4) according to [11]. To the tip 1 in Figure 2 (KI=0.07155231).

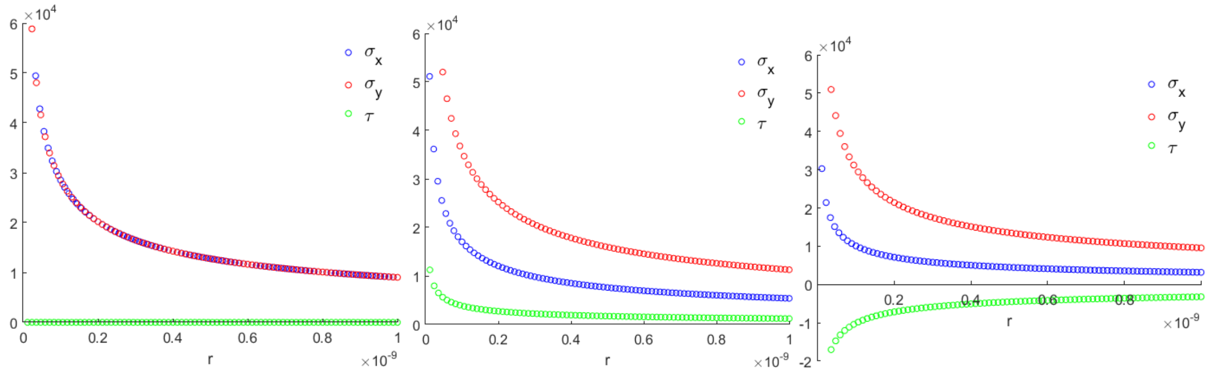
$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \tag{2}$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \tag{3}$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\left(\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right) \tag{4}$$

where *KI* is the SIF, *r* the distance to the tip and θ the angle as showed in Figure 4.

Figure 3 shows the stress field near the crack tip for three different angles used to the analysis in the micro element.



(a) (b) (c)

Figure 3: Stress field for different angles θ
a) θ=0° b) θ=45° c) θ=90°

As near the crack in the case of the LEFM the stresses tend to infinity near the crack tip, in order to calculate the maximum ones in the elastic stage it was used *r* as the distance of the Irwin's plastic zone (see Figure 4) resulting in:

$$2r_p = 1.42x10^{-8}\ m \tag{5}$$

The stresses field values are listed in Table 2.

Angle	σ_x	σ_y	τ
θ=0°	239.00	239.00	0.00
θ=45°	142.74	298.88	32.34
θ=90°	84.50	253.50	-84.50

Table 2: Stresses Fields

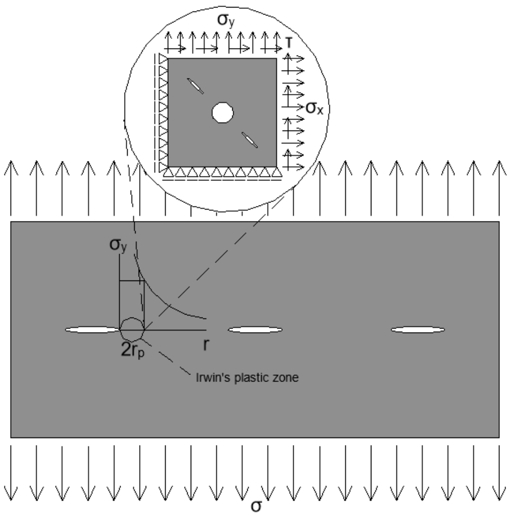


Figure 4: Illustration of the micro element for θ=0°.

The micro model is highlighted in Figure 5, which shows two pre-established cracks and a central circular hole. For the analysis, a BemLab2D model of a 1 cm square side element was adopted with the stresses calculated in Eqs. (2) to (4) and displacement constraint on the left and lower sides, with a central hole of radius 0.1 cm and two 0.1 cm cracks inclined 45°.

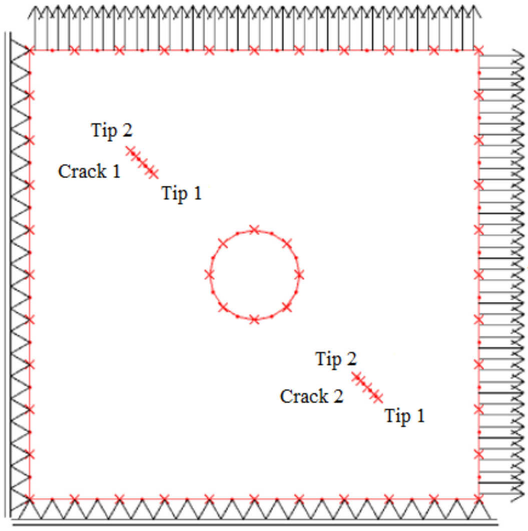


Figure 5 - Model of the Micro Element.

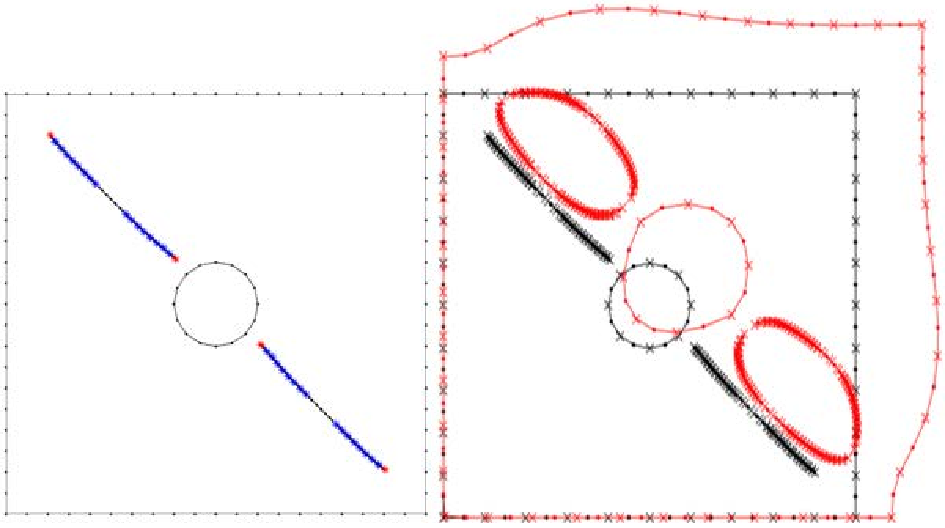
Once the stresses are obtained, the micro model is subjected to fatigue, obtaining results of compliance of the edges with each increase of crack (load cycles). For fatigue analysis via Paris Law, the coefficients C and m based on [12]. Considering R = 0.5, the values are C = 7.00 x 10^{-11} and m = 3.20. For the rivets were considered the one NAS 1097 AD4 model, 3.2 x 7 mm of aluminum material 2117-T4.

To represent the BEM mesh, 64 elements and 128 geometric nodes were considered. The continuous quadratic elements are arranged at the edges and in the central circular hole of the plate and discontinuous quadratic elements representing the cracks with a ratio of 0.2-0.3-0.3-0.2. The elements were distributed as follows: 10 on each outer edge adding 40, with distance 0.05 cm between them; 8 in the central circular hole and 8 in each crack, adding 16, according to Figure 5. In this analysis, eight increments of 0.02 cm each one was adopted, according to Figures 6a, 7a and 8a. The respective deformed meshes are show in Figures 6b, 7b and 8b. The animations of the crack propagation are in Table 3:

Angle	Propagation increments	Deformed mesh
θ=0°	https://youtu.be/G2YNFcojQPw	https://youtu.be/vftSVxFdE_Y
θ=45°	https://youtu.be/odRTjo4OntY	https://youtu.be/K875UDt8IMc
θ=90°	https://youtu.be/wmNxkXmxH2Q	https://youtu.be/Bgm7ru9cg7s

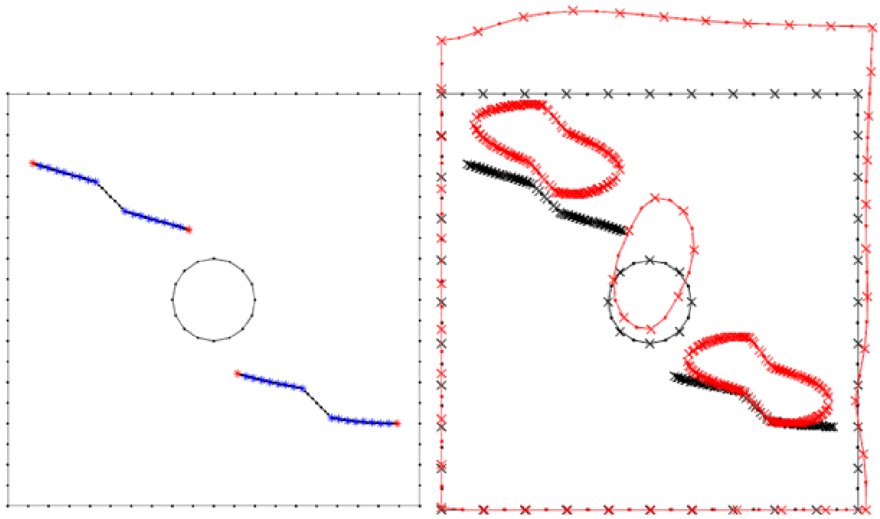
Table 3: Graphics Interchange Format (GIF)

In Figure 6a, for θ=0°, the propagation increments followed in the direction parallel to the crack, considering the symmetry of the problem and the field of stress, growing towards the hole, resulting in a symmetrical deformed mesh (Figure 6b). For θ=45°, the cracks have propagation in the diagonal direction of the crack (Figure 7a), since asymmetric stress field is submitted, the deformed ones for this element are shown in Figure 7b. For θ=90°, the results were similar to the previous one, but with diagonal crack increments more pronounced (Figure 8a), due to the asymmetry of the stress field, with strains shown in Figure 8b.



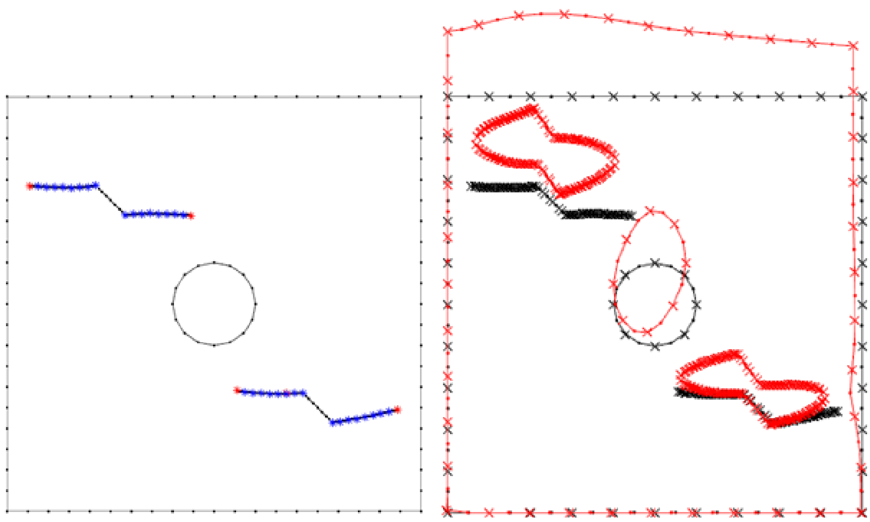
(a) (b)

Figure 6: Angle θ=0°: a) Crack propagation; b) Deformed mesh.



(a) (b)

Figure 7: Angle θ=45°: a) Crack propagation; b) Deformed mesh



(a) (b)

Figure 8: Angle θ=90°: a) Crack propagation; b) Deformed mesh.

4. Results

According to each increment there are the points for the construction of the fatigue life curve (N) x Compliance in (m/N) of both the right and upper edge, shown in Figures 9, 10 and 11 for θ=0°, 45° and 90°, respectively. It can be seen that as the crack propagates (number of cycles) compliance increases. This is due to the fact that the edge displacement rates increase gradually due to the loss of rigidity of the plate with the crack increments, so that when the number of cycles reaches about 10^6, the edge displacements are already quite amplified, resulting in high compliance. It is also seen Figure 9 that due to the symmetry of the plate layout, the graph of Crack 1 Tip 1 is equal to that of Crack 2 Tip 2 and that of Crack 1 Tip 2 is equal to that of Crack 2 Tip 1.

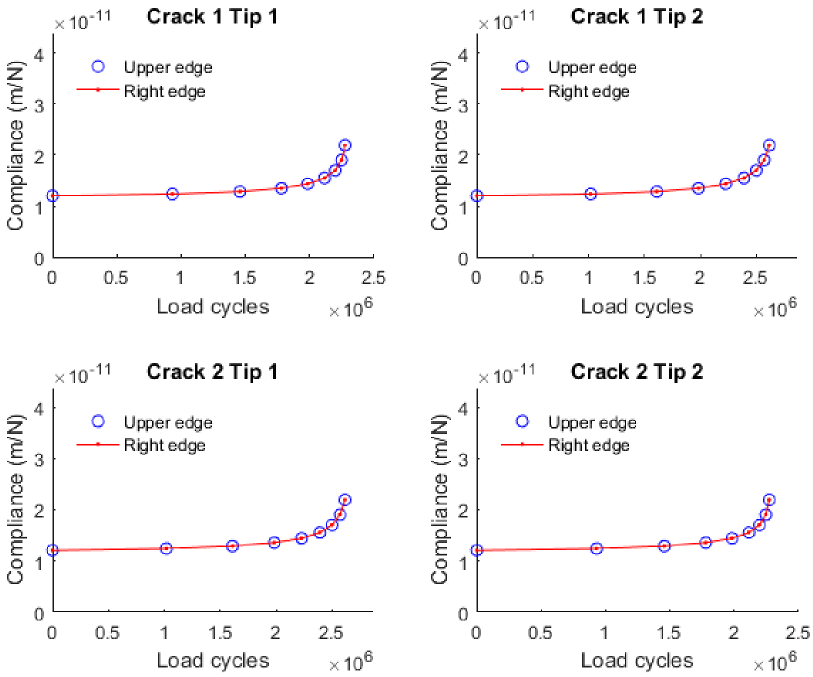


Figure 9: Load cycles x Compliance for θ=0°

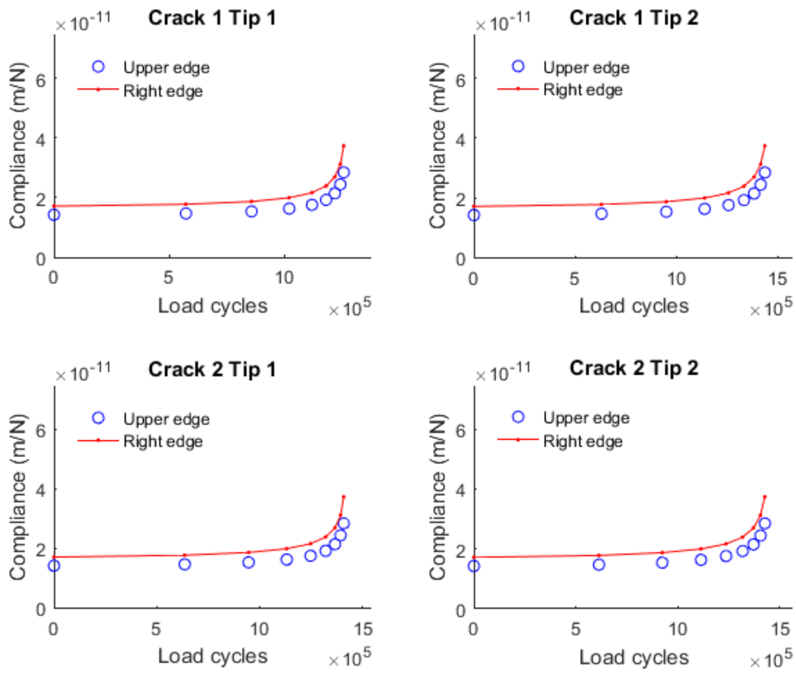


Figure 10: Load cycles x Compliance for θ=45°

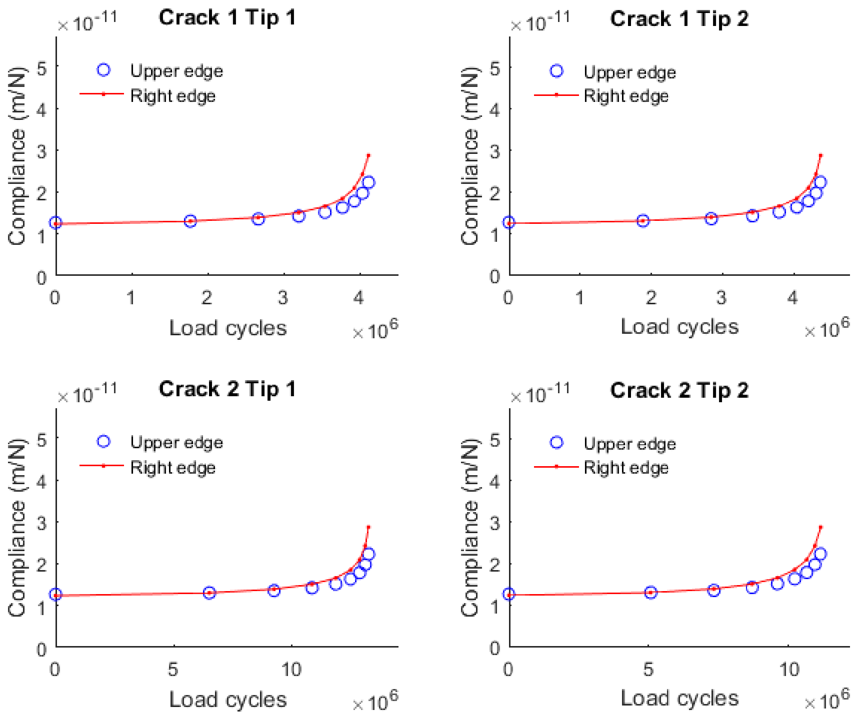


Figure 11: Load cycles x Compliance for θ=90°

5. Conclusions

This paper dealt with the influence of a macro panel in a micro element in different positions. For this, it was chosen treating an external load on a fuselage plate and analyzing regions near the rivets, which are critical areas for initiation and crack propagation. That influence was analyzed through the evaluation of the compliance of the micro element edges, due to the different stress fields in each position. Therefore, when the micro element is subjected to different stress fields, there are different results in crack propagation responses when subjected to the fatigue effect.

Regarding the use of software (BemLab2D and BemCracker2D), the results found for SIF validation were very close to the analytical ones with identical values up to the second decimal place. Therefore, it can be concluded that the use of these were satisfactory resulting in output data as expected.

The structures will respond to loading according to the type and magnitude of the applied load and its strength and stiffness. In order to establish whether the response is considered satisfactory depends on the requirements that must be satisfied. This includes structure safety against collapse, damage or deflection limitations, or other criteria. Each requirement is considered a limit state. The violation of a limit state is considered as an undesirable condition of the structure. This study of structural reliability considers the calculation and prediction of the probability of the violation of a limit state for a structural system at some stage during the useful life. In particular, structural safety is related to the violation of the Ultimate Limit State. Therefore, the obtained results can be used as parameters for a later study of structural reliability in aircraft fuselage.

6. Acknowledgement

The authors are grateful to the Brazilian National Research Council (CNPq), to the Brazilian Coordination for the Improvement of Higher Education (CAPES) for the supporting funds for this research and to Federal District Research Support Foundation (FAP-DF). The authors also thank the Graduate Programme in Structural Engineering and Civil Construction in the Department of Civil and Environmental Engineering at the University of Brasilia.

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